Nonlinear dynamics of self-pulsing all-solid-state lasers

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Report Documentation Page

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Abstract.

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Report – main text – Introduction.

The subject of *rogue waves* (also *freak waves*) has recently become a hot topic in many areas, including such dissimilar fields as Optics, Ecology and Stock Exchange. The subject was born in Oceanography, and refers to the observation of waves of large amplitude that, although rare, appear more often than one would expect from a Gaussian distribution. "Optical rogue waves" were defined for the first time, as large fluctuations in the light intensity, in the edge of the spectrum produced in a micro-structured optical fiber pumped with femtosecond laser pulses [1].

The causes and mechanisms of formation of these fluctuations, in Oceanography as in the other fields, are a subject of research. In consequence, it is unknown whether they share a single description or not. The point in common is the long tailed distribution. In Optics, this situation has led to a controversy on whether the term "optical rogue wave" is appropriate, or not. We do not want to take a position in this controversy. Hence, we will use the neutral term "extreme event" (EE) in this Report. Yet, we think pertinent to note that the Nonlinear Schrödinger Equation (NLSE) has been attempted to describe the formation of oceanic rogue waves [2-3], and that the same equation is used in the customary approach to lasers with a saturable (i.e.,

nonlinear) absorber [4]. Therefore, at this point of the research, it should not be discarded the phenomena to have in common more than it seems, especially in the case of the Kerr-lens-mode-locked Ti:Sapphire laser.

In this Project, we studied the EE observed in two types of solid-state lasers:

1) The all-solid-state (i.e., diode-pumped) Nd:YVO$_4$ laser, passive Q-switched with Cr:YAG as the saturable absorber (SA). Typically, it emits pulses of 10-100 ns duration at a repetition rate of 5-20 KHz, at a wavelength of 1064 nm. This device is small, efficient, economic and robust, and is used in many applications. Knowing the mechanism of formation of EE in this system may lead to control their emission. This would allow having laser pulses of high intensity at times of interest, without having to scale up the whole device. It would be an important advantage in some uses of interest for the Air Force, for example, in laser rangefinders or target illuminators aboard small unmanned flying vehicles. This laser corresponds to the case of a "slow" SA.

2) The Kerr-lens-mode-locked (KLM) Ti:Sapphire laser. Typically, it emits pulses of 20-200 fs duration at a repetition rate 50-200 MHz, at a wavelength in the 800 nm range. It is the most widespread source of ultrashort laser pulses nowadays. It is also close, in mathematical terms, to the problem of the oceanic rogue waves (through the tentative common description with the NLSE). Increasing the knowledge on the dynamics of this device is of practical interest in itself. Besides, it is hoped that the results of the observations on this laser (which are much faster and easier to record than in the high seas, not to mention the change of the control parameters) may provide some clues to the solution of the problem of the oceanic rogue waves. This laser corresponds to the case of a "fast" SA.

In the following lines, we briefly report the results of our studies performed on the EE observed in these two types of lasers. Also, in the all-solid-state laser with loss modulation. This activity was not planned originally, but it appeared convenient as a way to understand the more complex case of the all-solid-state laser + SA. Publications and other scientific contributions presented during the Project are listed at the end. They provide further details on the studies briefly reported here.

1) EE in the Nd:YVO$_4$+Cr:YAG laser (more details in publications #1, #4 and #5).

We designed and built a diode-pumped Nd:YVO$_4$+Cr:YAG laser prototype with a large Fresnel number. The cavity has a V-shape and the Cr:YAG crystal (which is the SA) is placed in the arm where the mode diameter has the largest variation (see Figure 1). This allows adjusting the saturation parameter by simply displacing the Cr:YAG closer or farther from the output mirror, with a micrometer translation stage. Several Cr:YAG crystals with different transmissions were used. The active medium Nd:YVO$_4$, instead, is always the same: 3x3x1 mm^3, 1% Nd and coatings appropriate for longitudinal pumping with a 2W CW laser diode at 808 nm. In general, this prototype operates in the self-pulsing (passive Q-switched) regime.

Depending on the position of the Cr:YAG inside the cavity, uniform Q-switching, period doubling, bifurcations' cascades and chaotic regimes are observed. In the chaotic regimes, there are situations with and without EE. The classical approach to describe this system [5] predicts the bifurcation cascade and even the chaotic regime, but not the EE. Our earliest observations indicated that EE arise easier in this system if the Fresnel number is large, suggesting that EE are due to multimode dynamics.

We recorded time series of the pulse energies (with and without EE) with fast photodiodes and a digital oscilloscope. After processing the series to take into account only the maxima of the pulses, we calculated their dimension of embedding (dE) and the values of the Lyapunov exponents (this was not possible for *all* the experimentally recorded series, probably due to noise). Chaotic and hyperchaotic series were observed. EE were prone to appear in series where dE was larger than the value of 4 of the classical approach in [5].
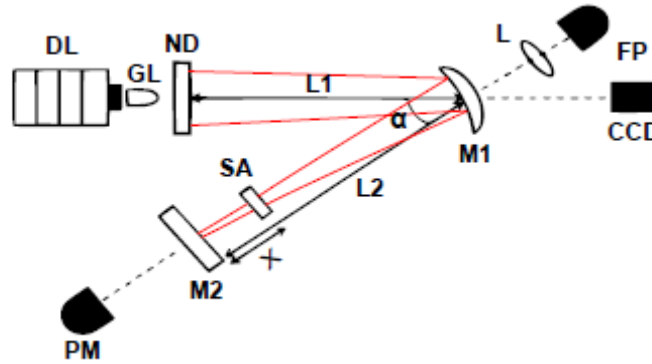

Figure 1: Scheme of the laser prototype. LD: pump laser diode, GL: GRIN lens, ND: Nd:YVO$_4$ active medium, M1: spherical mirror (R=250 mm), M2: output mirror (plane), SA: Cr:YAG crystal, T=90%, L: lens, FP: fast photodiode, CCD: camera, PM: power meter, α=20°, L1=130 mm, L2=75 mm. The position x of the SA is adjustable with a micrometer translation stage, to obtain different dynamical regimes.

We drew return maps for the energy and time (i.e., the separation between successive pulses) variables, and heterodyne interferograms with a modified Mach-Zehnder and a CCD camera. We also recorded the self-correlation and the mutual information of the time series obtained at different points in the output beam. The purpose was to determine the importance of the multimode dynamics in the formation of the EE.

We observed that not only the pulse energy, but that also the variable "time between successive pulses" can be chaotic, and that it can also display EE (i.e., there are extraordinarily long times between pulses). Noteworthy, the energy-EE are *not* anticipated by a time-EE. This implies that there is some unknown mechanism of energy storage. As energy-EE appear in large Fresnel number configurations, we speculate that this mechanism is related with regions of the active medium that are not depopulated by the average pulses due to the destructive interference among transversal modes (building in this way a Lippman grating). These regions would be effectively depopulated by the EE pulses. This idea is supported by the observation that energy-EE are followed by a long time before the next (non-EE) pulse.

The regime with EE shows partial transversal decoherence (Fig.2, Left). Besides, the self-correlation of the time series obtained at different points in the laser spot decays in the regimes with EE. This indicates that EE in this system are related with spatio-temporal chaos. Yet, we also observed that the time series is more regular and predictable in the neighborhood of an EE than an average pulse, even inside the same time series (Fig.2, Center and Right). This suggests that the process of formation of EE follows a deterministic dynamics, and that there is, in consequence, some hope to predict and, eventually, to control the EE in this system. As it is mentioned in the Introduction, this possibility is of practical interest.
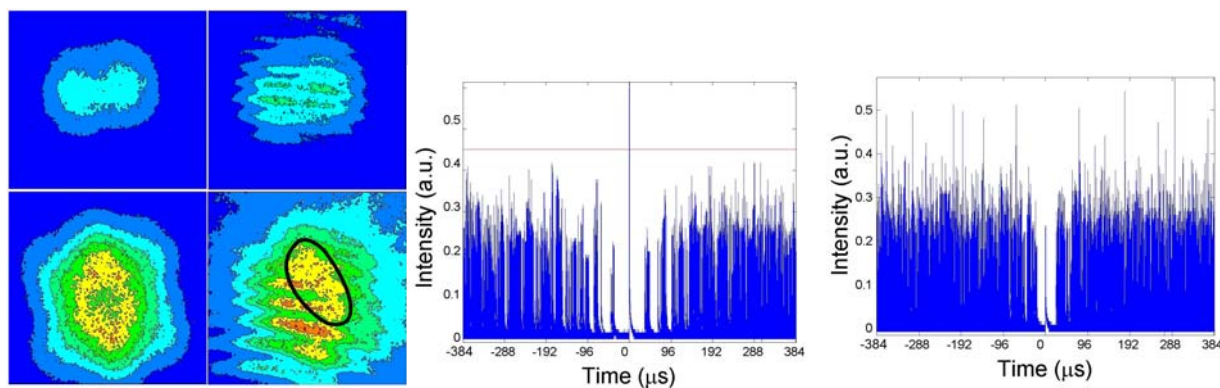
Figure 2: **Left:** heterodyne interferograms of the output beam (the laser spot without interference is on the left) for different dynamical regimes. Up: intermittent chaos with no EE, the interference figure covers the whole spot, the field is transversally coherent. Down: chaos with EE, the region surrounded with the black line does not display interference lines, hence, it is not coherent with the reference beam. **Center:** superposition of 112 oscilloscope traces centered in each of the EE of a time series with a total of 10^4 pulses. The horizontal line indicates the position of the EE threshold for this series. **Right:** superposition of 112 oscilloscope traces centered in pulses of average intensity, extracted from the same time series as in the figure at the center. The dynamics becomes unpredictable much faster for the average intensity pulses than for the EE.

   Due to the time resolution of our camera, the interferograms as the ones in the Fig.1 average the images formed by many pulses. Yet, we manage to know from the energy-return maps that the EE are not associated with a determined, fixed spatial pattern. It remains to know if these "EE-patterns" are uniformly brighter than the average or, instead, if they include "hot spots", that increase the total recorded energy (like, say, a supernova increases the luminosity of a whole galaxy). We foresee obtaining single-pulse images of the output laser beam to determine which alternative is the correct one.

   This part of the Project is the core of the plan for the Ph.D in Physics (in progress) of Carlos Bonazzola, to be presented at the Universidad de Buenos Aires.

2) EE in the Ti:Sapphire laser (more details in publications #2 and #3).

   The EE in this laser take the form of pulses of high energy. The time separation between pulses is fixed, and given by the laser cavity's round trip time. Our measurements were performed on an owner-made KLM Ti:Sapphire laser of standard X-configuration (see Figure 3), CW pumped at 532 nm by a 5W diode-pumped and frequency doubled $Nd:YVO_4$ commercial laser (Verdi). The main control parameter is the group-velocity-dispersion (GVD), which is adjusted by displacing one or both of the intracavity prisms perpendicular to the cavity's axis. This laser is not placed in our lab, but in the *Laboratorio de Electrónica Cuántica* of the Universidad de Buenos Aires.

   The KLM Ti:Sapphire laser is known to display three coexistent modes of operation: continuous wave output (named P0), transform-limited fs pulses (P1) and positive-chirped pulses (P2). It is possible to go from one mode to the other by slightly perturbing the laser (say, by tapping the positioning device of any one of the mirrors). The laser also evolves spontaneously from one mode to the other, in a time scale of minutes, most probably due to mechanical noise and thermal drifts. The modes P1 and P2 have their own characteristic road to chaos: P1 through quasi-periodicity, P2 through intermittency. Be aware that "mode" here means a dynamical way

to operate, and not a spatial oscillation eigenstate, as the usual Gauss-Laguerre modes. The laser is controlled here to oscillate always in a single transversal, nearly TEM_{00} mode.
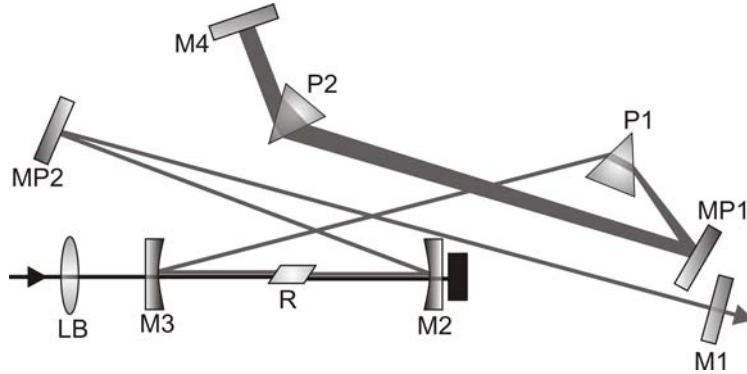

Figure 3: Scheme of the Ti:Sapphire laser. LB: pump focusing lens (f=10cm), $M_{2,3}$ spherical mirrors (R=10 cm) $MP_{1,2}$ plane HR mirrors, $P_{1,2}$ pair of prisms. Distances (in mm): M_3-R=R-M_2=50, M_2-MP_2=140, MP_2-M_1= 465, M_3-P_1=297, P_1-MP_1=198, MP_1-P_2=415, P_2-M_4=109. The prisms' positions are adjusted to get negative total GVD.

Our group pioneered the observation of EE in this laser (in fact, in any laser of standard design operated under normal conditions) [6]. Two intriguing features were noted: one, the EE are observed in the chaotic regime of the mode P2 only. Two, the time separation between successive EE, as measured in numbers of intermediate non-EE pulses, is always a simple combination of the numbers 11 and 12 (which we called "magic numbers").
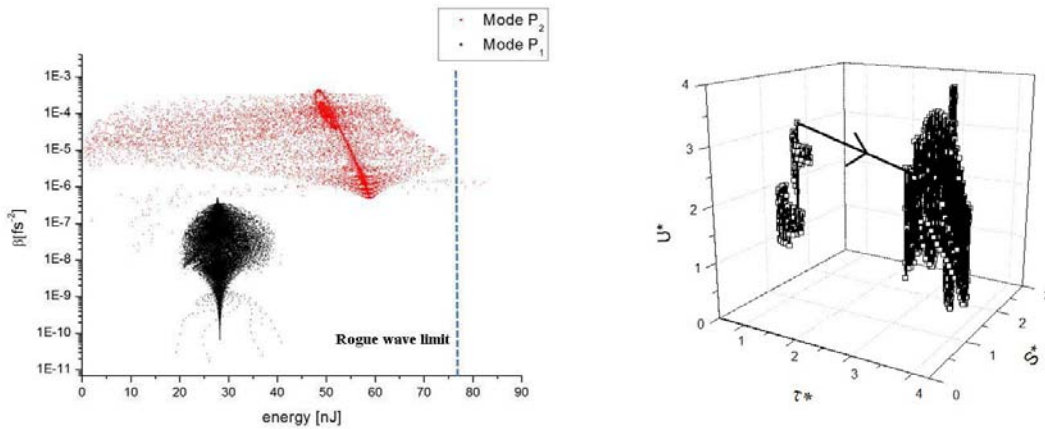

Figure 4: **Left:** SPM and energy of each pulse in a chaotic time series with 10^5 mode-locking pulses. Almost all the pulses in the mode P2 (in red) have a larger value of SPM than even the largest in P1 (in black). The spiraling orbit corresponds to a quasi-periodic excursion of the mode P1. **Right:** fast evolution of the system from P1 to P2 when the laser parameters are above the "modulational-instability-like" threshold. The transition to P2 occurs after 218 round trips ($\approx$2.5 μs in real time), total length of the run: 10^4 pulses.

During this Project, by using a well-tested description of this laser with a five-variables iterative map [7], we were able to explain both intriguing features. In the Figure 4 (Left) the self-phase-modulation (SPM) and energy of each pulse in a series of 10^5 are plotted, for each mode of

operation (P1: black, P2: red). It is noticeable the spiraling orbit corresponding to a quasi-periodical excursion, typical of the P1 mode. The EE threshold for the mode P2 is plotted as a vertical dotted line. There are 331 red points (they seem fewer because of the scale of the figure) to the right of this line, indicating that there are 331 EE in this series. The mode P1, as said, displays no EE and is much less spread in the energy variable. Even though the P2-pulses are spread both in SPM and energy, the EE all have nearly the same value of SPM which, in addition, is relatively low for the mode P2 but higher than any pulse in the mode P1. This value of SPM extends to the left, inside the region of the non-EE pulses, and forms a sort of "limit line". We hypothesize that this value of SPM, about 10^{-6} fs^{-2}, corresponds to some kind of threshold.

In general terms, the Modulational (or Benjamin-Feir) instability of a periodical solution of the NLSE occurs when the nonlinearity overwhelms the dispersion scaled with the frequency of the periodical stable solution. In our case, the nonlinearity is the SPM and the GVD is a constant parameter (the stable mode-locking regime is the periodical solution), so that it is reasonable to expect a dynamical threshold associated to the minimum value of the SPM in a given mode. This analogy is important for the purposes of this Project, because the Modulational Instability is suspected to be involved in the formation of oceanic rogue waves.

Even though no pulse in the P1 mode has a SPM above 10^{-6} fs^{-2} in the Fig.4, some of them are just at the border. In principle at least, a small increase in the pulse energy may allow the P1 mode to cross the threshold. We therefore increase the small signal gain in the numerical simulation for the P1-map (to increase the pulse energy) and looked for EE. In fact, a 40% increase in the small signal gain does produce EE in the mode P1 too. Yet, EE are not observed in the mode P1 in the practice, because P1 is unstable for this value of the gain. This is best seen in the Fig.4 on the right, where the numerically obtained trajectory of the system in the phase space is plotted (the variables are: U: energy, S: inverse of the spot area, τ: pulse duration, they are all scaled to their values at the fixed point of P1). Even though the system is forced to start in the neighborhood of the fixed point P1, it rapidly evolves into P2. Translated to the real time scale, the system does not remain in the mode P1 more than 3 μs, too short to be observed. By the way, note the vertical excursions (the vertical axis corresponds to the energy) in the mode P2, which corresponds to EE, and that the crossing from one mode to the other occurs precisely after a high energy excursion (the early stage of an EE?) in P1.

We conclude that the formation of EE in this laser is related with the crossing of a threshold in the SPM value, which has similarities with the Modulation Instability of the NLSE.

Regarding the "magic numbers", we develop a description with a simplified iterative map, which has the form of a (perturbed) Moebius map in the complex plane. The analysis of the solutions of this map, and its comparison with the real laser's design parameters, show that the magic numbers correspond to the geometrical periodicities [8] of the empty cavity (or "cold cavity", i.e., with no nonlinear effect taken into account). Therefore, the observed dynamics are the residuals of the periodic orbits when subjected to two opposite perturbations: one is dissipative (or contractive of the phase space), due to the unavoidable presence of transversal apertures inside the cavity. The other perturbation is expansive, due to the self-focusing in an appropriate cavity's design, which is found to be precisely that of the real one. Finally, we check that if the cavity's design is changed, the values of the magic numbers change accordingly.

3) EE in the Nd:YVO₄ laser with loss modulation (more details in draft #6 at the end of this Report).

The dynamics of the formation of EE in the transverse multimode Nd:YVO$_4$+Cr:YAG laser, as it was explained in the Section (1), are complex. We then proposed to study the formation of EE in a simpler system, in order to get some clues to understand the complete process. The underlying hypothesis is that EE are due to the occurrence of an *external crisis*. In few words, an external crisis is, in a multistable system, the collision of an unstable orbit belonging to one solution with the chaotic attractor belonging to another one. The collision produces an abrupt increase of the volume of the phase space that can be reached from the chaotic solution. Recent theoretical developments show that EE should appear in this case, for parameters' values attainable with a solid state laser with modulated losses [9].

We then designed and constructed a laser prototype similar to the one sketched in the Fig.1. The active medium is again a Nd:YVO$_4$ 3x3x1 mm^3, 1% doped crystal pumped by a 2W CW laser diode at 808 nm, and a V-shaped cavity. There are important differences, however, with the prototype used in the Section (1) (which, by the way, has not been dismantled): the Fresnel number is adjusted to be low (the beam is nearly single transversal mode M^2 ≈1.1), there is no SA crystal, and an electro-optical modulator (EOM) is inserted into the cavity. The EOM introduces a polarization rotation proportional to the voltage V$_{mod}$ provided by a signal generator. The Nd:YVO$_4$ active medium ensures that the field is linearly polarized, so that the rotation introduced by the EOM is equivalent to a change in the cavity losses. The EOM is driven at a sinusoidal frequency *f* close to the frequency of the relaxation oscillations, which is measured here to be 111 ± 1KHz. As before, the laser output is detected with a fast photodiode and time series recorded in a digital oscilloscope. The amplitude of the modulation V$_{mod}$ (i.e., the output voltage from the signal generator) is the control parameter.
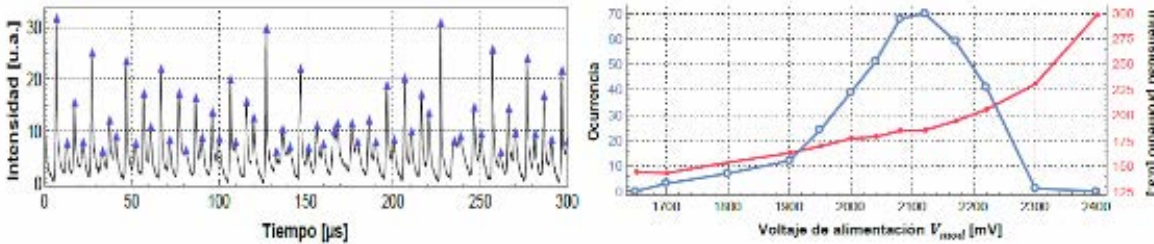

Figure 5: **Left:** A section of the oscilloscope trace recorded for V$_{mod}$= 1.7 V, *f*=100 KHz, Pump power= 1.024 W. The triangles indicate the position of the maxima of the pulses, which compose the time series that is numerically studied. **Right**: Number of EE and average intensity as a function of the loss modulation amplitude near the crisis, *f*=100 KHz, P=1.024 W.

Depending on the value of V$_{mod}$, the laser output is observed to be CW, periodically pulsed, and chaotically pulsed with and without EE. At low values of V$_{mod}$, pulsed regimes of different periodicities are observed to coexist. Uniform pulsing, 2-period, 3-period, until 6-period regimes are stable. Higher 8- and 10-period are also observed, but they are rather unstable. It is possible to pass from one pulsed regime to the other by blocking and unblocking the cavity, or by tapping one of the mirrors. Transitions among the different regimes occur spontaneously too. These observations confirm that the system is multistable.

As V_{mod} is increased, bifurcations are observed and the output becomes aperiodic. As before, the peaks of each pulse compose a time series (see Fig.5, Left) which is numerically analyzed. For a typical time series, we obtain dE=5 (the surrogate series has no definite value of dE) and the Lyapunov exponents: 0.32, 0.11, -0.08, -0.30, -0.76. The regime is hence dissipative and (hyper)chaotic, but no EE are observed (V_{mod} = 1.6V). As V_{mod} is increased, EE begin to appear. The number of EE is maximum at 2.12 V, then decreases, and EE disappear at 2.3V, being the regime always chaotic (see Fig.5, Right). This is precisely the behavior predicted for this system as it passes through an external crisis [9].

The study of the behavior of the pulses in the neighborhood of an EE (similar to the one on the right side of the Fig.2 obtained for the laser + SA) shows that, also in this case, EE are more regular and predictable than the average pulse. This suggests that the evolution of EE occurs into a well defined manifold in phase space, supporting the hypothesis of their deterministic nature, and giving some hope to the goal of predicting and controlling them.

In conclusion for this Section, the laser with modulated losses appears as a promising "toy system" to get insight into the more general properties of the process of formation of EE in all-solid-state lasers.

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Archival publications produced during this Project:

#1 - C. Bonazzola, A. Hnilo, M. Kovalsky and J. Tredicce, "Features of the extreme events observed in the all-solid state laser with a saturable absorber"; *arxiv.org/abs /1506.02014* (2015).
#2 - A.Hnilo, M.Kovalsky, M.Agüero and J.Tredicce, "Characteristics of the extreme events observed in the Kerr lens mode locked Ti:Sapphire laser", *Phys. Rev. A* **91**, 013836 (2015).
#3 - A.Hnilo, M.Kovalsky and J.Tredicce, "On the features of the optical rogue waves observed in the Kerr-lens-mode-locked Ti:sapphire laser", *arXiv.org/abs/1403.5210* (2014).
#4 - C.Bonazzola, A.Hnilo, M.Kovalsky and J.Tredicce, "Optical rogue waves in the solid-state laser with a saturable absorber"; *IEEE Xplore paper 3022515* (2013).

#5 - C.Bonazzola, A.Hnilo, M.Kovalsky and J.Tredicce, "Optical rogue waves in the all-solid-state laser with a saturable absorber: importance of the spatial effects", *J.Opt.* **15**, 064004 (2013).
#6 - N.Granese, A.Lacapmesure, C.Bonazzola, M.Agüero, M.Kovalsky, A.Hnilo and J. Tredicce, "Extreme events and crises observed in an all-solid-state laser with modulation of losses"; *in preparation* (2015), find a copy of this draft at the end.

Posters presented at the annual meetings of the *Asociación Física Argentina*:

- "*Caracterización de regímenes dinámicos con eventos extremos (rogue waves) en un láser de estado totalmente sólido*"; C.Bonazzola, A.Hnilo, M.Kovalsky and J.Tredicce (2014).
- "*Causas en la aparición de eventos extremos (optical rogue waves) en un láser de Ti:Zafiro de femtosegundos*"; A.Hnilo, M.Kovalsky and J.Tredicce (2014).
 – "*Números mágicos en la aparición de eventos extremos (rogue waves) en un láser de Ti:Zafiro de femtosegundos*"; A.Hnilo, M.Kovalsky and J.Tredicce (2013).
 – "*Eventos extremos (rogue waves) en un láser de estado totalmente sólido con absorbente saturable: importancia de los efectos espaciales*"; C.Bonazzola, A.Hnilo, M.Kovalsky and J.Tredicce (2013).

Talks at international meetings:

- "Extreme Events: a consequence of a crisis"; J.Tredicce, A.Hnilo, M.Kovalsky, C.Metayer, T.Quiniou and J.Rios Leite; "IPS15 Conference", Singapore, 4-6 March 2015.
- "Extreme events in Q-switched lasers"; F.de Aguiar, J.Rios Leite, C.Metayer, T.Quiniou, A.Serres, J.Tredicce, M.Agüero, C.Bonazzola, A.Hnilo, M.Kovalsky, A.Lacapmesure and N. Mirón; Workshop "Dynamic Days", Viña del Mar, Chile, 3-7 November 2014.
- "Extreme events in Q-Switched lasers"; J.Tredicce, F. Aguiar, J.Rios Leite, C.Metayer, A.Serres, T.Quiniou, A.Hnilo and M. Kovalsky; paper NTh3A.7, "Advanced Photonics", Barcelona, Spain, 27-31 July 2014.
- "Extreme Events in the Dynamical Behavior of Laser Systems"; S. Barland, M. Giudici, A. Hnilo, M. Kovalsky, C. Metayer, T. Quiniou, A. Serres and J.R.Tredicce; W-AWE2014: "Workshop on Abnormal Wave Events", 5-6 June 2014, Nice, France.

What follows is a text still in preparation (#6):

Extreme events and crises observed in an all-solid-state laser with modulation of losses.

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We present experimental data supporting the hypothesis that extreme events (or optical rogue waves) in a laser with a modulated parameter are related with multi-stability and external crises. We discuss the predictability time of extreme events compared to the predictability of any other event during the chaotic behavior of the system. We experimentally show that the predictability of an extreme and rare event is larger than theoretically expected. We compare such time with theoretical and experimental measurements of the positive Lyapunov exponents. Furthermore, we explore theoretically a possible protocol to maximize the predictability of an extreme event.

During the last years several optical systems have been used as test benches for the study of extreme and rare events [1-4]. Such events have been also called optical rogue waves for their high amplitude, much higher than expected in "normal circumstances". Furthermore, it is already accepted that optical rogue waves may appear as a consequence of very different types of dynamics. They can be expected relatively frequent in linear systems, in some sense induced by random boundary conditions and the possibility of multiple interferences [5-6]. They have been predicted and observed in nonlinear dynamical systems, for example, after the development of a modulational instability [7-10]. In other words, extreme events (EE) appear in complex systems, and most of them are reasonably studied only through statistical methods and represented by an infinite number of variables. However, some systems can be modeled by ordinary differential equations. The simplest system of this category may be a laser with a modulated parameter [11-14]. The appearance of rogue waves in such system was studied theoretically [14] and the appearance of EE was associated to an external crisis of a strange attractor. EE have been theoretically predicted to exist in a CO_2 or solid-state laser with a modulated parameter [13]. The numerical simulations indicate the appearance of EE to be caused by an *external crisis*, i.e., the collision of an unstable orbit belonging to one of the solutions of the multistable system, with the chaotic attractor belonging to another solution. The collision produces an abrupt increase of the region that can be reached in the phase space, and hence, to EE. As the control parameter gets farther from the point of collision the number of EE decreases, even if the average amplitude of the pulses increases. In this paper, we present experimental evidence in support of this explanation of the origin of EE in an all-solid state with modulation of losses.

The quantitative definition of an EE usually is: *a)* amplitude higher than twice the "significant wave height" or "significant intensity" $I_{1/3}$ [7,8,14], which is the average calculated among the set of the 1/3 highest events in the series [15]. An event is then considered "extreme" if its *abnormality index* AI ≡ $I_{event}/I_{1/3}$ is larger than 2. Alternatively: *b)* amplitude higher than four times the standard deviation. These two definitions can be coincident or not, depending on the form of the distribution. In this paper, we use the second alternative unless specified otherwise.
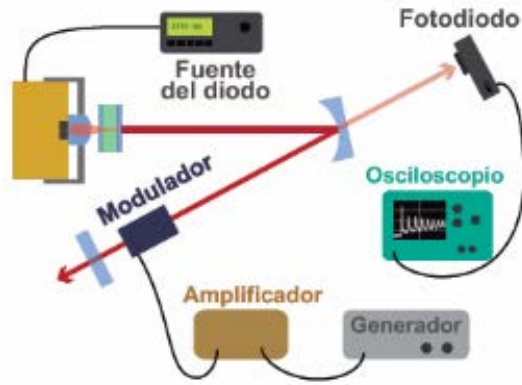

Figure 1: Scheme of the experiment.

The scheme of our modulated all-solid-state laser is shown in the Fig.1. A $Nd:YVO_4$ crystal is pumped with power P with a CW diode laser at 808 nm. The $Nd:YVO_4$ material ensures that the field oscillating into the optical cavity is linearly polarized. A standard V-shaped cavity produces a waist near the output (plane) mirror, where an electro-optic modulator (EOM) is placed. The EOM introduces a polarization rotation proportional to the voltage V_{mod} provided by the signal generator. As the field is linearly polarized, this rotation is equivalent to a change in the cavity losses. The EOM is driven at a sinusoidal frequency *f* near the frequency of the relaxation oscillations, which is measured here to be 111 ± 1KHz. The laser output is detected with a fast photodiode and time series recorded in a storage oscilloscope. The typical output power is 200 mW for P=1.5W. The beam has a uniform transversal shape, $M^2 = 1.1 \pm 0.05$. Depending on the values of the control parameters P, V_{mod} and *f*, the laser output is observed to be CW, periodically pulsed, and chaotically pulsed with and without EE. With f≈100 KHz and low values of V_{mod}, pulsed regimes of different periodicities are observed to coexist. Uniform pulsing, 2-period, 3-period, until 6-period regimes are stable. Higher 8- and 10-period are also observed, but they are rather unstable. It is possible to pass from one pulsed regime to the other by blocking and unblocking the cavity, or by tapping one of the mirrors. Transitions among the different regimes occur spontaneously too, in a time range of the order of the minute. The pulses have duration between 0.8 and 1.2 μs. These observations mean that the system is multistable. In this respect, this system behaves the same as the CO_2 laser with modulated losses [16].

As V_{mod} is increased, bifurcations are observed and the output becomes aperiodic. The zoom of a typical aperiodic oscilloscope trace is displayed in the Figure 2. The peaks of each pulse compose a time series. For the complete time series of this example (which is made of 89602 peaks), the value of the dimension of embedding and the Lyapunov exponents are calculated to be dE=5 (the surrogate series has no definite value of dE), λ_i= 0.32, 0.11, -0.08, -0.30, -0.76. The regime is hence dissipative and hyperchaotic.
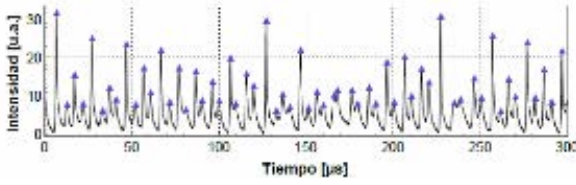
Figure 2: A section of the chaotic time series recorded for V_{mod}= 1.7 V, f=100 KHz, P=1.024 W. The triangles indicate the position of the maxima of the pulses, which compose a time series.

Inside the chaotic regime, EE are observed for some values of the parameters. In the Figure 3, histograms of the distribution of the pulses' amplitudes are shown as V_{mod} is varied. The regime is always chaotic, but it displays no EE at 1.8V, it does at 2.12 V and again it does not at 2.3V. This is the behavior predicted for this system near an external crisis [13].
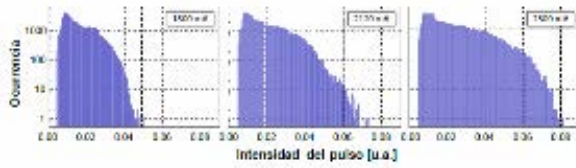

Figure 3: Histograms of the pulses' amplitudes for increasing loss modulation amplitude. The dotted line indicates the threshold for EE.

In the Figure 4, we plot the number of observed EE as V_{mod} is scanned through the crisis. Compare with the Figure 8 in the Reference 13. As predicted, the number of EE increases as the crisis is approached, and decays after the system has climbed to the next "step" of higher intensity. Note that the average output intensity increases monotonically.

In a numerical simulation of the semiconductor laser with optical feedback in the short-cavity regime [17], EE are calculated to be more predictable than the average chaotic pulse. The same feature is observed here. In the upper part of the Figure 5, the traces corresponding to the 74 EE of the time series corresponding to the peak in the Fig.4 are displayed. The pulses neighboring the EE occur at nearly the same time and have nearly the same intensity. Naturally, they "blur" as the distance to the EE increases. For the average pulse instead (lower part of Fig.5) the characteristics of the neighboring pulses immediately become unpredictable.
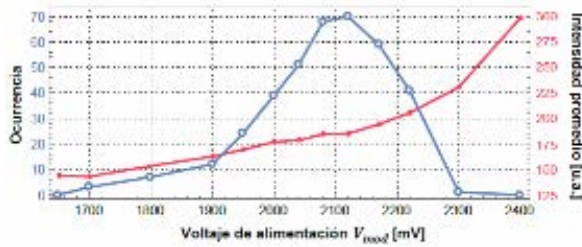

Figure 4: Number of EE and average intensity as a function of loss modulation amplitude near the crisis, f=100 KHz, P=1.024 W.
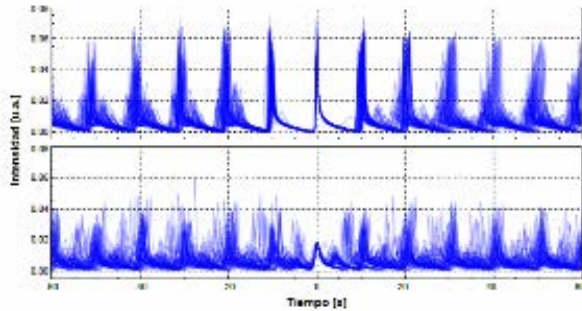
Figure 5: Superposition of 74 EE and the same number of pulses of intensity near the average intensity, both extracted from the same time series, which corresponds to the maximum in the Fig.4.

This suggests that the evolution of EE occurs into a well defined manifold in phase space. This result supports the hypothesis of a deterministic nature of the observed EE, and give some hope to the goal of predicting and controlling them.

The study of the EE in the laser with a modulated parameter, as a subject of dynamical systems, is interesting by itself. Besides, it will lead to a deeper understanding of the operation of these lasers and, eventually, to an improvement of their performance. This simple system may also provide a convenient test bench to study the general features of the phenomenon of EE. For, lasers dynamics evolve instantaneously (at the human's timescale) and their control parameters are easy to adjust.

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Alejandro Hnilo

Program Manager
The AFOSR Program Manager currently assigned to the award

James Fillerup

Reporting Period Start Date

03/27/2013

Reporting Period End Date

03/31/2015

Abstract

The Project involved the study, both experimental and theoretical, of extreme events (EE, sometimes named Optical Rogue Waves) in two types of self-pulsing lasers: 1) all-solid-state (i.e., diode-pumped) Nd:YVO4+Cr:YAG ("slow" saturable absorber); and 2) Kerr-lens-mode locked Ti:Sapphire ("fast" saturable absorber). The main tool is the analysis of the time series of the laser pulses and of the images of the laser spots.
Regarding (1), observations on a specially designed and constructed prototype showed the existence of EE in the pulse energy and also in the time separation between pulses. The two types of EE are uncorrelated: a high energy pulse is not preceded by a longer pumping time. Therefore, the problem is to identify the "reservoir" for the energy-EE. Correlations were identified between the spatial complexity of the laser spot, the Fresnel number of the cavity, the dimension of embedding of the time series and the appearance of EE.
Regarding (2), two coexistent modes of operation are observed: transform-limited pulses (P1) and chirped pulses (P2). EE are observed only in P2. We found that EE arise after a threshold similar to the modulational instability is crossed. EE exist in P2 only, because P1 is unstable for the parameters' values above that instability threshold. If the system is forced to start near P1, it evolves into P2 before EE can be observed in the practice. Finally, the observed privileged distances in the separation between successive

EE are the residuals of the "cold" cavity periodicities, perturbed by the opposite tendencies of an expansive Kerr nonlinearity and contractive aperture losses.

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#2 - A.Hnilo, M.Kovalsky, M.Agüero and J.Tredicce, "Characteristics of the extreme events observed in the Kerr lens mode locked Ti:Sapphire laser", Phys. Rev. A 91, 013836 (2015).

#3 - A.Hnilo, M.Kovalsky and J.Tredicce, "On the features of the optical rogue waves observed in the Kerr-lens-mode-locked Ti:sapphire laser", arXiv.org/abs/1403.5210 (2014).

#4 - C.Bonazzola, A.Hnilo, M.Kovalsky and J.Tredicce, "Optical rogue waves in the solid-state laser with a saturable absorber"; IEEE Xplore paper 3022515 (2013).

#5 - C.Bonazzola, A.Hnilo, M.Kovalsky and J.Tredicce, "Optical rogue waves in the all-solid-state laser with a saturable absorber: importance of the spatial effects", J.Opt. 15, 064004 (2013).

#6 - N.Granese, A.Lacapmesure, C.Bonazzola, M.Agüero, M.Kovalsky, A.Hnilo and J. Tredicce, "Extreme events and crises observed in an all-solid-state laser with modulation of losses"; in preparation (2015), find a copy of this draft at the end of the Report.

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none.

Change in AFOSR Program Manager, if any:

none.

Extensions granted or milestones slipped, if any:

none.

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LRIR Title

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Program Officer

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